Flexible carbon capture

Workshop overview, structure, desired objectives

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July 30, 2019

Why we're here

Give feedback to ARPA-E on this potential program

Begin building a research community

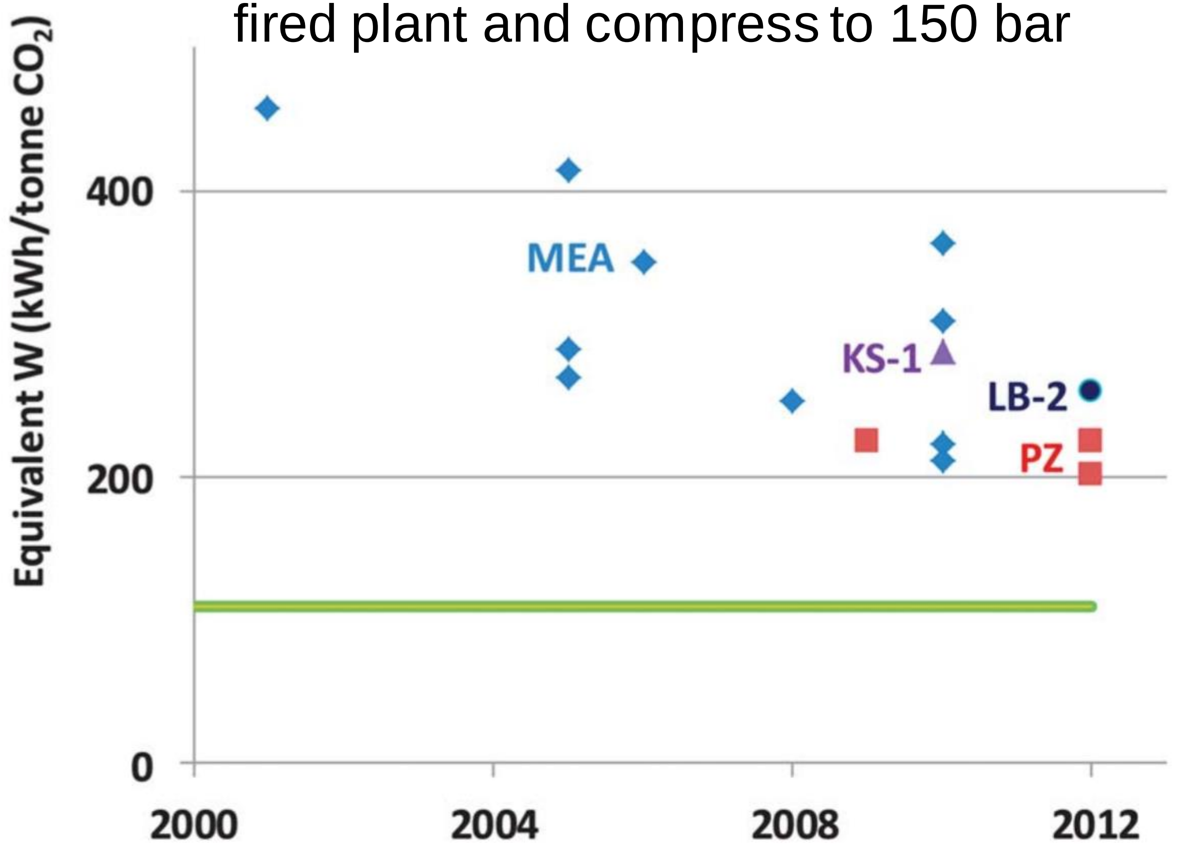
Outline

- **What problem(s) we're trying to solve**
- Updated technical content since the webinar
- About this meeting

Reminder of some context

- Renewables are changing how power plants operate
  - Ramping
  - Turndown
  - Capacity factor
- Firm, low-carbon resources could reduce the cost of deep decarbonization by 10-62%*
- There's been great progress in CCS development, but focus has been baseload coal plants

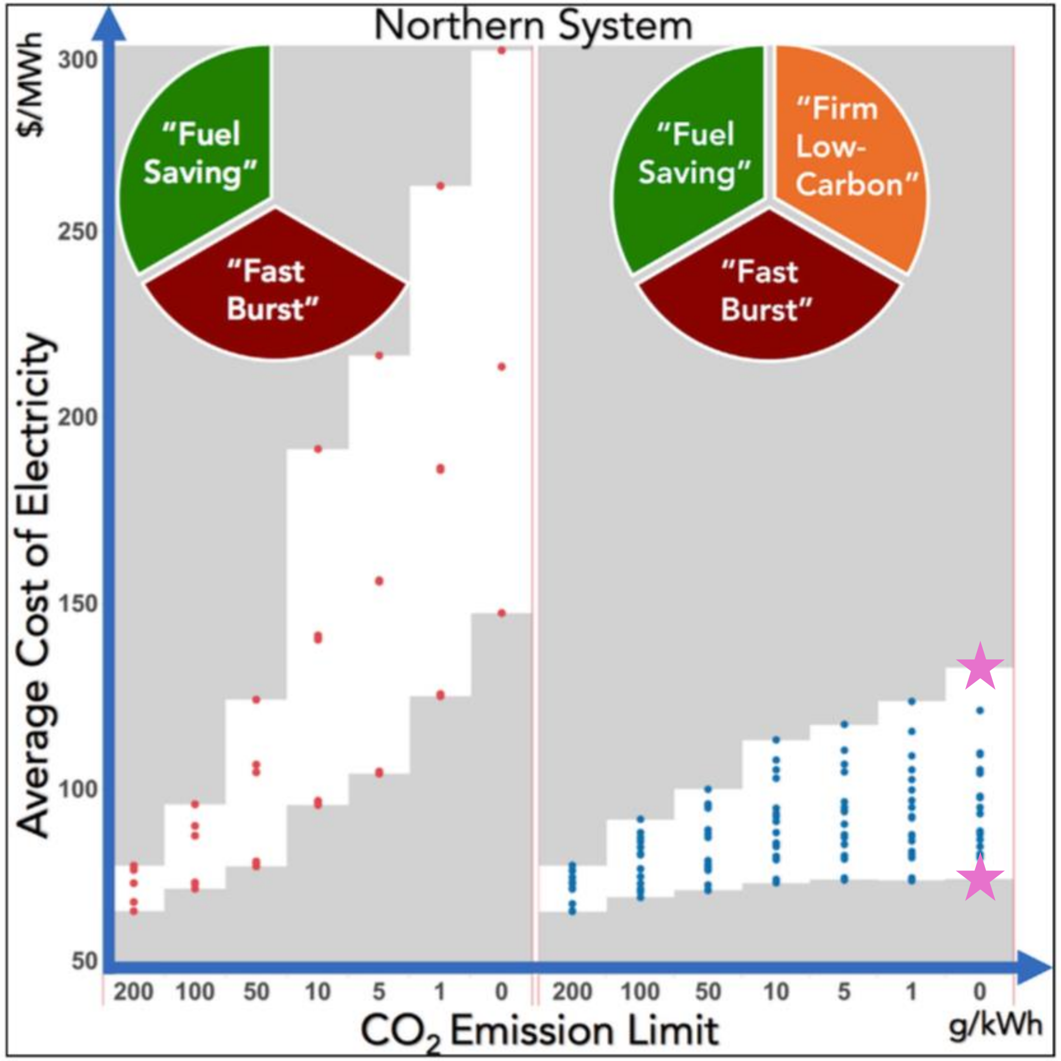
Work to separate CO2 from a coal-fired plant and compress to 150 bar



M.E. Boot-Hanford, et al., *Energy Environ. Sci*. 7, 130-189 (2014)

*Sepulveda, et al., *Joule* 2, 1–18 (2018)

Reminder of some context



Technology examples

- Solar, wind
- Storage, demand response
- Nuclear, CCS, geothermal

Would you rather pay this…

…or this?

Sepulveda, et al., *Joule* 2, 1–18 (2018)

What problem are we trying to solve?

Long-term, aspirational

Decarbonize electricity generation as much as possible, as quickly as possible, and as cheaply as possible

Reduce the cost of firm, low-carbon resources like CCS and nuclear

Optimize the design and operations of CCS-equipped power plants to reflect the changing power grid

Near-term, specific

Reduce CCS capex and energy requirements; develop unit ops that enable flexible operation

There are several questions here

For a CCGT plant on a grid with lots of renewables, energy & capacity markets, and a price on carbon, design a CO2 capture and compression process with:

1 The lowest C price and capacity payments so that $NPV_{CCS} = NPV_{no\ CCS}$ & that NPV is non-negative

2 Same as #1, but now include constraint on CO2 intensity

3 Same at #1, but now include constraint of negative CO2 intensity

What is the minimum carbon price needed to install CCS at CCGT plant?

What is the design and cost of CCS at CCGT plant to achieve a certain integrated degree of capture?

Is there a way of removing CO2 from the atmosphere that's cheaper than a standalone DAC process?

Nearer-term ⟷ Longer-term

Our plan to tackle these problems

1. Represent future grid conditions

Tuesday AM: Electricity markets overview, capacity expansion models, gas turbine capabilities, and group-wide Q&A

2. Identify valuable CCS attributes to fit that future

Tuesday PM: Presentations, breakout session 1

3. Find optimal process design and operations

Wednesday AM: Presentations, breakout session 2

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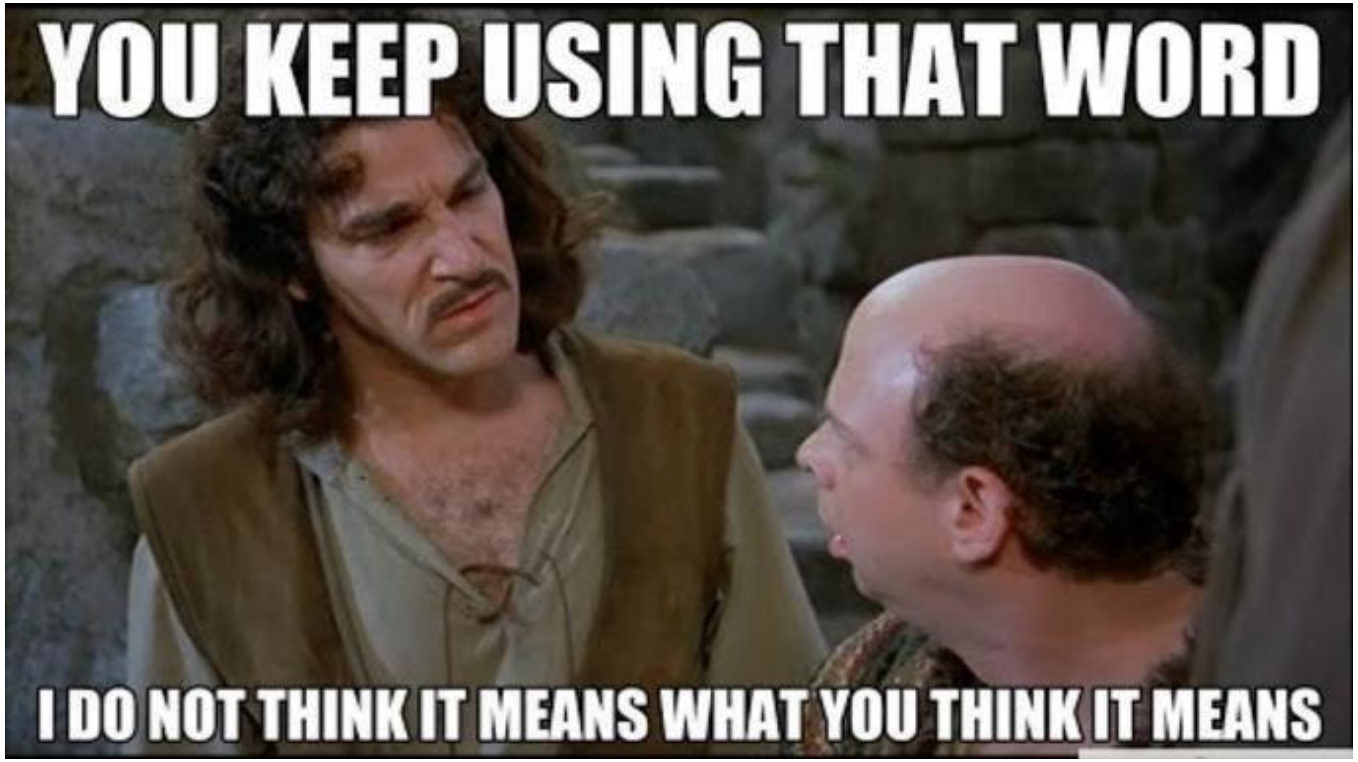
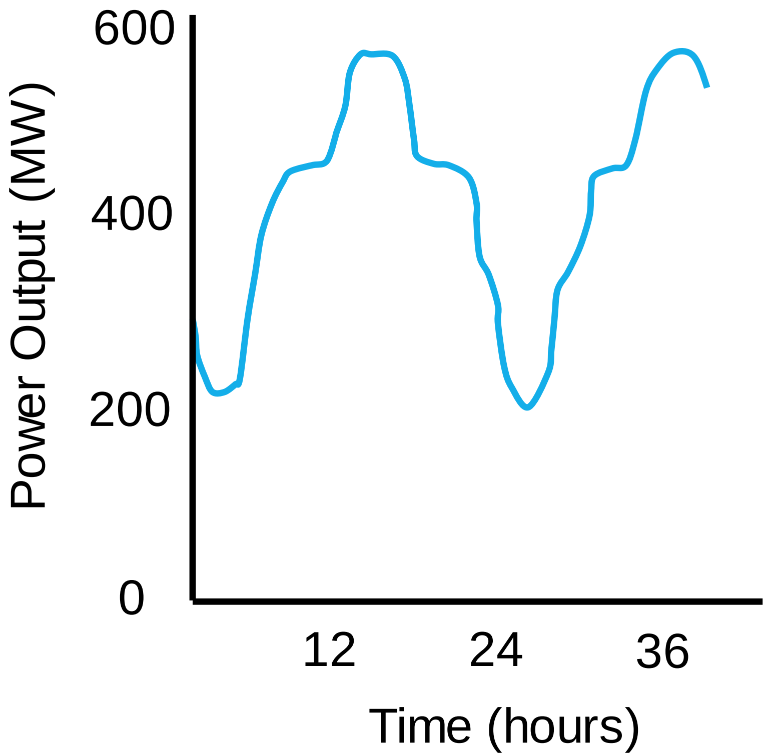
Another problem I'm trying to solve: terminology

When it comes to "flexible CCS"…



What flexible CCS might look like

Power plant output (today)



Reduce or cut off heat to reboiler if plant wants steam

Store rich and lean solvent to time-shift CCS

Capture plant ramping: power ramping affects capture unit via increase/decrease flow rates of

- Flue gas
- Solvent
- Hot water

Optimizing capex / efficiency tradeoffs

Modular unit ops

Rightsizing the capture unit

Categories adapted from M. Bui, et al., Int'l. J. Greenhouse Gas Cont. 79, 134-153 (2018)

Unpacking LCOE

$$\text{LCOE} = \frac{\text{(Capital cost)(capital recovery factor) + Fixed O\&M}}{\text{(Capacity factor)(net plant capacity)(8766)}} + \text{Variable O\&M} + \text{(Heat rate)(Fuel cost)}$$

CHANGING WHAT'S POSSIBLE

Unpacking LCOE

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Does it get dispatched?

Unpacking LCOE

Does it stay online
(annual operating profit > fixed costs)?

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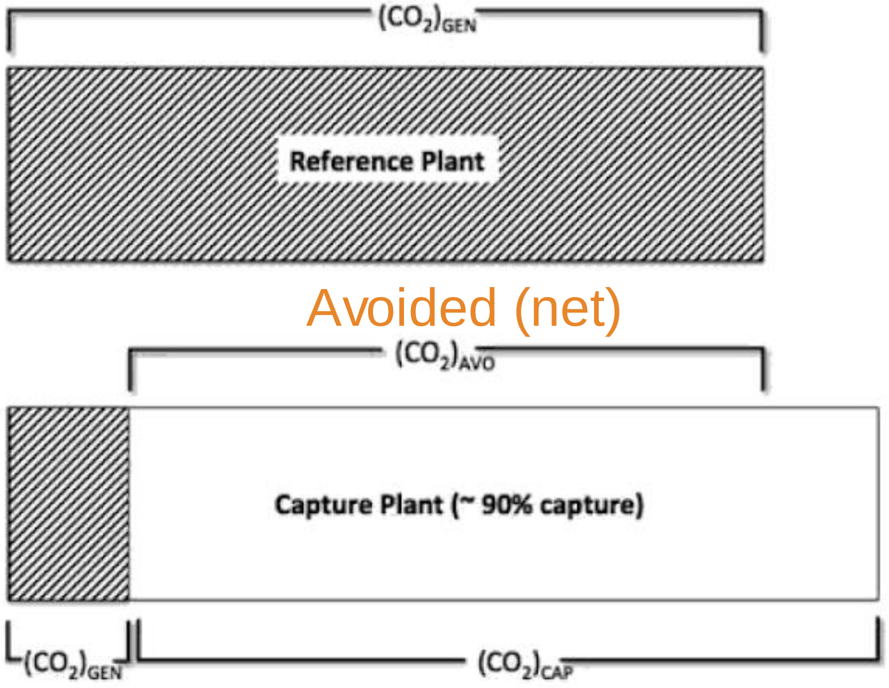
Does it get built?

Does it get dispatched?

Different metrics

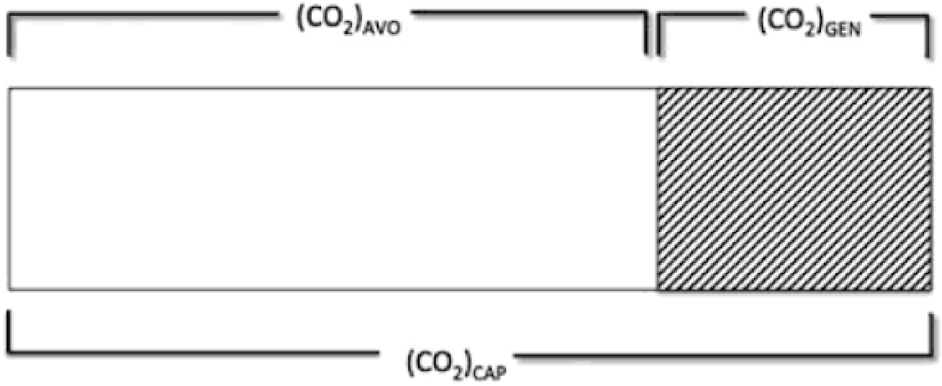
Power plant



Captured (gross)

Direct air capture

Avoided (net)



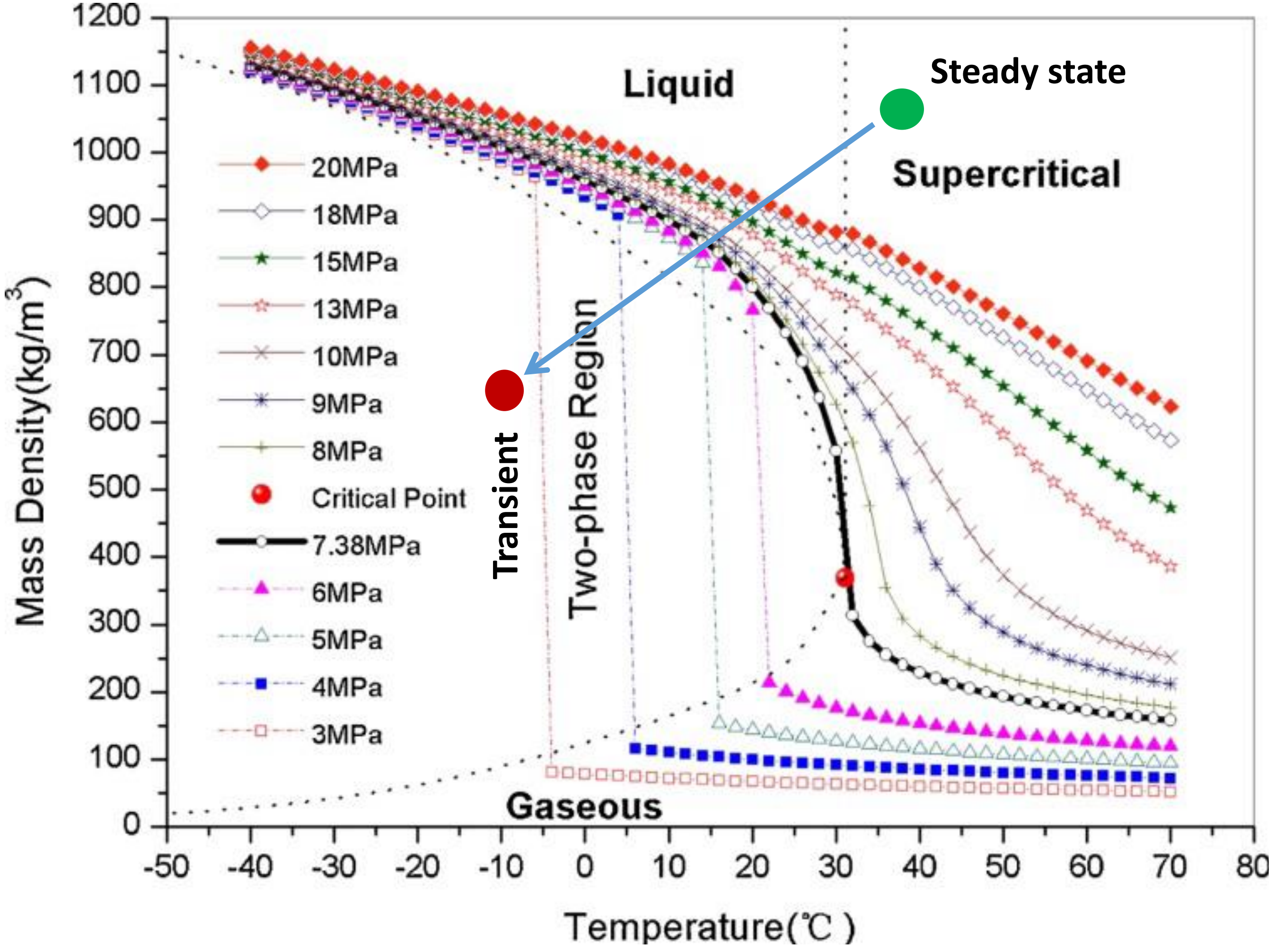
Captured (gross)

Carbon price: dollars per ton emitted

NPV = Today’s value of expected cash flows minus today’s value of invested cash

Intermittent CO2 supply could create downstream complications

CO_2 phase diagram showing operating points for **steady state** vs. **transient** CO_2 supply



Transient CO2 supply could cause

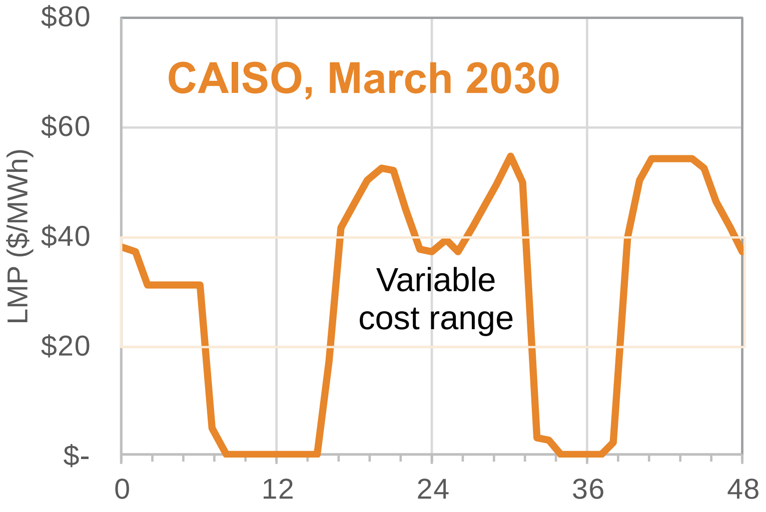
- Solids formation: potential blockage of injector outlet
- Thermal stress and tension: potential fracture of pipe casing

R.J. Samuel, H. Mahgerefteh, Int'l. J. Chem. Eng. App. 8, 319-326 (2017)
M.D. Jensen, et al., Energy Procedia 63, 2715-2722 (2014)

Current vision for this potential program

Phase 1

Economic Inputs



Workflow

High-level process flow diagram

Build plant, capture models, add costing

Design, operations optimization

Dynamic modeling

Results, Impact

What is a precise, succinct, and descriptive way to capture the questions I posed several slides ago?

Phase 2

Shock-resistant HX

Flexible ASUs

Modular absorber, regenerator designs

Compressors with variable inlets

Capex intensification

Multi-hierarchical models bridging future markets structures, dispatch operations, and plant unit ops

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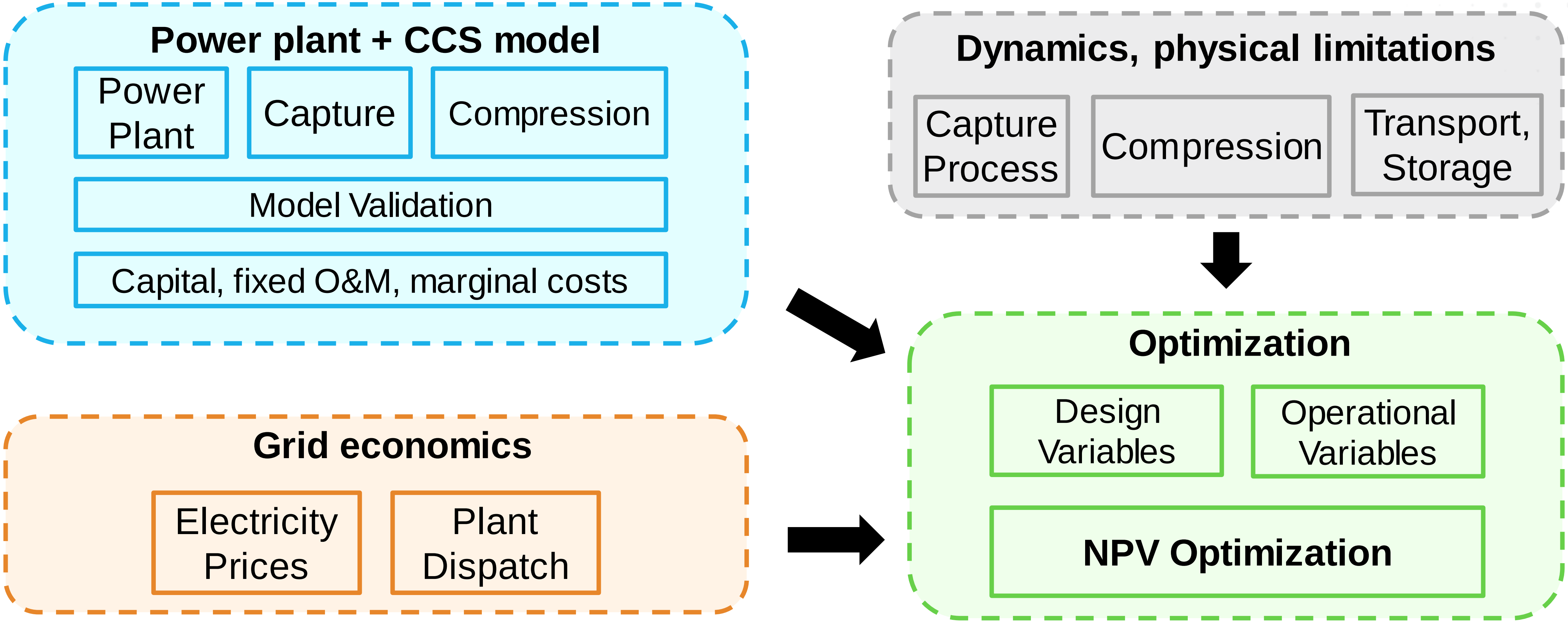
Building a research community

ARPA-E programs bring together research teams to solve tough problems



Surrogate-based optimization

Courtesy Shima Hajimirza, Texas A&M

Data generation → **Surrogate building** → **Optimization**

- Model specific design of experiment: determination of representative points using random sampling, latin hypercube, …

- Selected from a wide range of methods with various nonlinearity: polynomial regression to multilayer neural networks.
- The surrogate performance is evaluated by validation (out-sample) error.

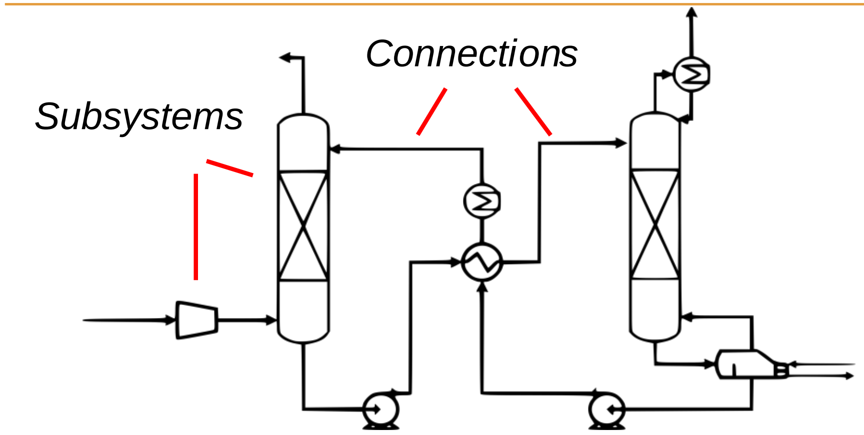
- Common optimization methods include:

  - Gradient based: quasi-Newton,
  - Heuristic: simulated annealing, genetic,
  - Bayesian,…

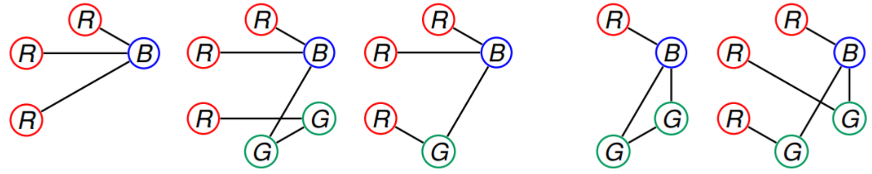
Example: found potential for 50% increase in external quantum efficiency of thin film solar cells with <u>5-20x less</u> computational time

M. Kaya, S. Hajimirza, Nature Scientific Reports 8, 8170 (2018)

Design methods for process architecture optimization



“Standard” solvent process



Graph-based representation of alternative architectures

- Process architecture decisions can encompass **what subsystems/technologies** to include in a CCS system as well as **their connections**
- Graph-theoretic and other frameworks have been developed for both representation and generation of new process candidate architectures
- Methods for exploring these process architecture decisions**:** Enumeration algorithms, rule-based approaches, machine learning frameworks, etc.

- A class of methods known as **control co-design (CCD) methods** fully capitalize on plant-control coupling to achieve **system-optimal performance** through optimization
- Trends towards incorporating implementable closed-loop control and comprehensive uncertainty treatment

Courtesy Dan Herber, Colorado State University, https://www.danielherber.com/

Other examples of optimization

- Flexible design representations to improve competing design objectives simultaneously: YH. Lee, et al., J. Mech Design 139, 053401 (2017)

- Dimension-reduction techniques for high-fidelity representations and models yet computationally-efficient: D.J. Lohan, et al., Structural & Multidisciplinary Optimization 55, 1063-1077 (2017)

- Adaptive surrogate modeling to reduce # of hi-fi simulations while preserving accuracy: Y.H. Lee, et al., Structural & Multidisciplinary Optimization 60, 99-116 (2019)

- Use advanced design tools to identify high-performance, non-obvious designs, J., Choe, J. Kim, Composite Structures 158, 333-339, (2016)

Workshop guidelines

- We want your feedback; multiple opportunities to provide it, including afterwards
- We are NOT trying to come to consensus
- Typical brainstorming etiquette applies
- Go easy on the sales pitch in breakout sessions

Acknowledgements

Meeting Planners
Nancy Hicks
Danielle Weingarten

Tech-to-Market
Max Tuttman

Technical Team

Laura Demetrion

Dan Hancu

Gokul Vishwanathan

Breakout Session 1 – Potential process solutions

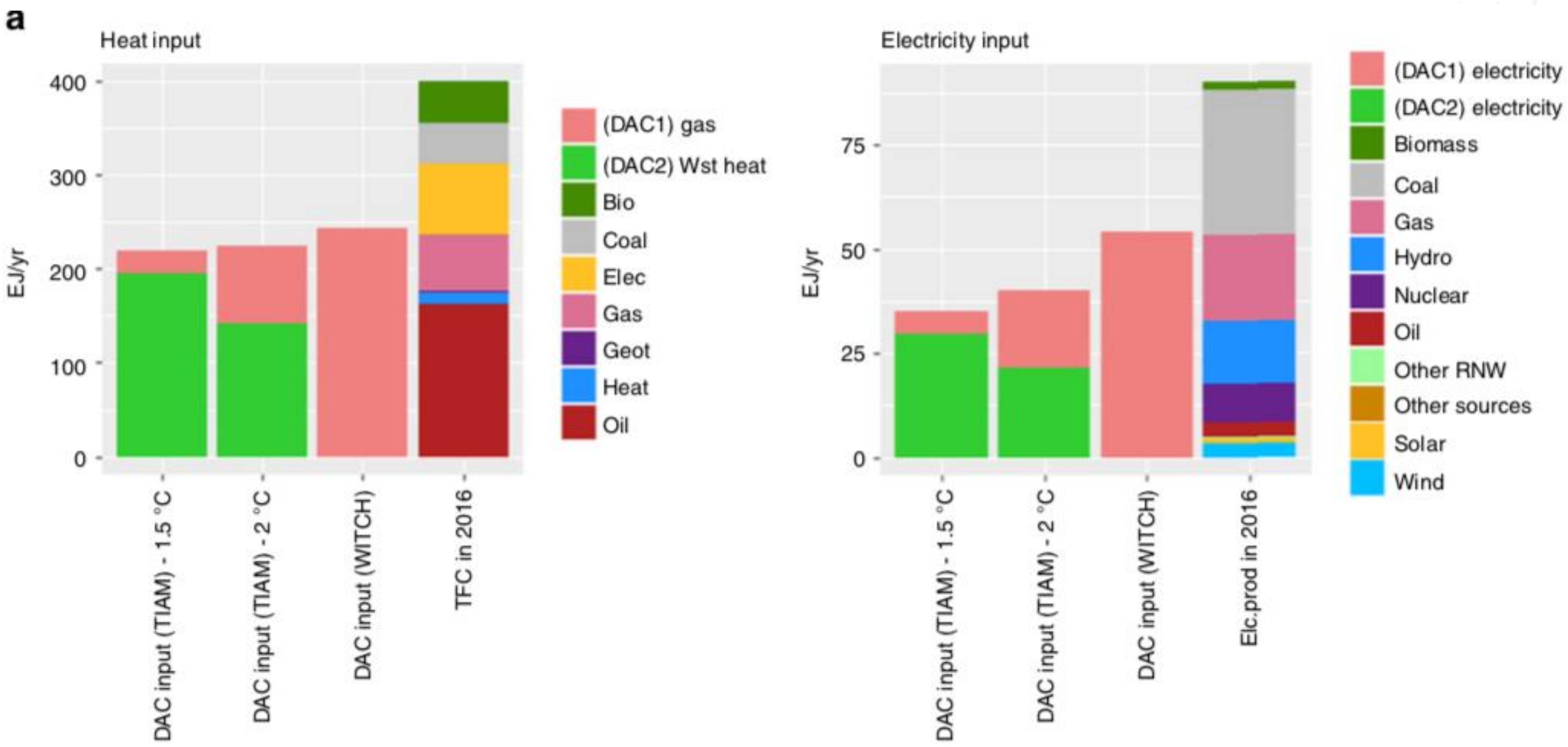
Attributes that CCS-equipped plant might need to be relevant to the future grid

- Low capex; marginal cost good enough to get dispatched
- Reconfigurable/modular: the optimal capture rate will likely increase over time
- Ability to quickly change CO2 capture rate and power required (think: asset to be traded just like the power plant)
- Shift load to periods of low LMPs
- Help remove CO2 from the atmosphere

Potential program scope

	In scope	Out of scope
CO_2 source	CCGT, maybe industrial sources	Coal-fired power plants (Heavy focus from NETL, Coal FIRST program)
“Expanding the box” solutions	Storage, direct air capture	Hydrogen via SMR or electrolysis, P2X, CO_2 to fuels or valuable chemicals, selling specialty gases

Why do I keep talking about DAC?



G. Realmonte, et al., Nature Communications 10, 3277 (2019)

Two Things to think about when it comes to DAC integration

normally
off

- Remember Shand: 90 to 96% capture when plant turns down to 62%
- If a CCGT spends time at 20-30%, how much would it cost to increase capture rate to > 99%?
- How many credits could be earned?

normally
on

- What might the economics look like for a power plant co-located with a dedicated DAC facility?

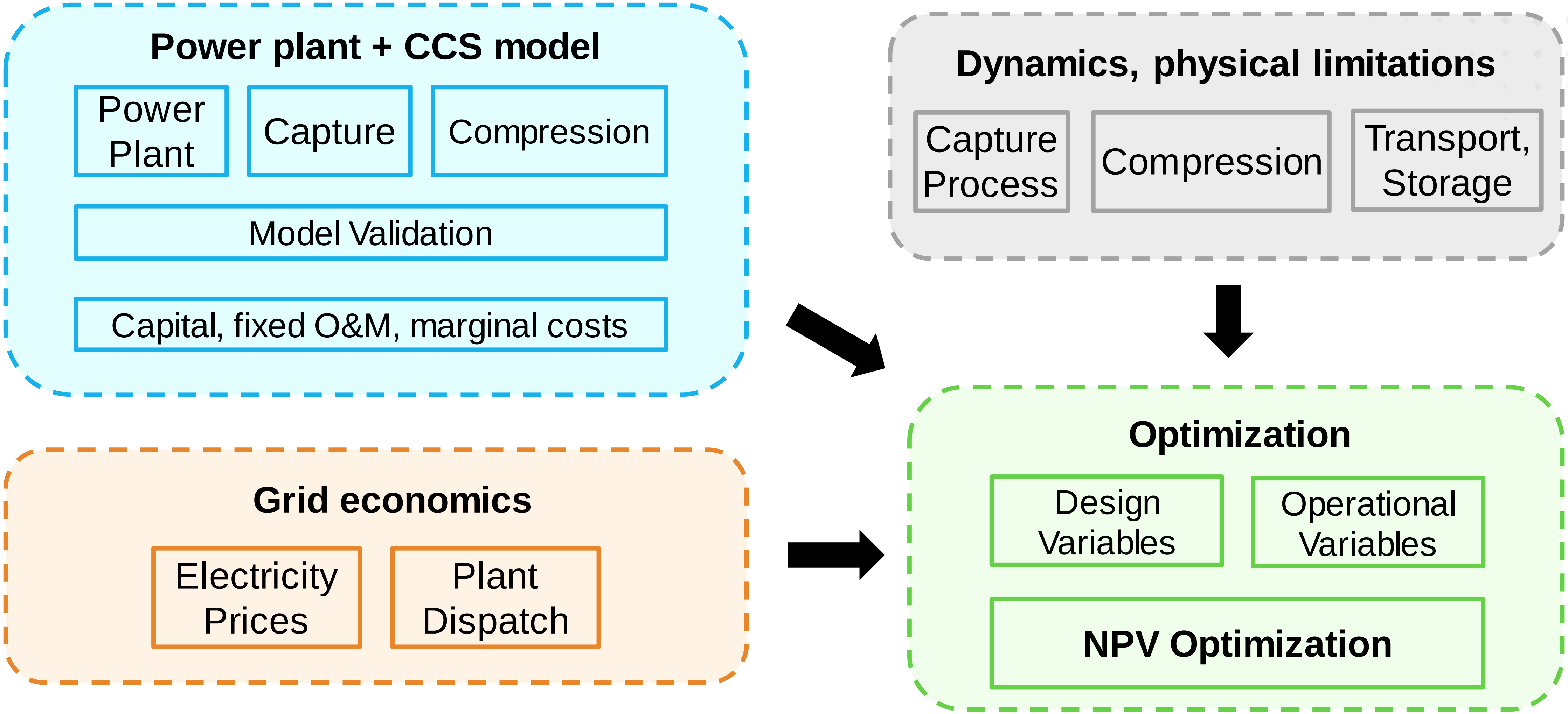
Both ideas share CO2 compressor, pipeline, injection well

arpa·e
CHANGING WHAT'S POSSIBLE

Breakout Session 1 – Questions

- For expected ramp rates and turndown, can current CCS process designs handle that?
- Given these prompts, what technology attributes do you think will be most valuable?
- Are there CO_2 capture technologies that are particularly amenable (or not) to these needs?
- How compelling is the DAC integration idea?

Breakout Session 2 – Finding optimal processes



Breakout Session 2 - Questions

- How to balance breadth (lots of parameters being optimized) and depth (sufficiently detailed solutions that actually have meaning)?
- What is the optimal amount of LMP data to specify in a potential FOA?
- How will information be passed between the different models?
- How can we compare monoethanolamine (MEA) to less mature capture technologies, including dynamic model validation?